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Generic Assessment of Radiation Exposures to Workers in a Portable Smelter and to the Surrounding Population

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OAK RIDGE NATIONAL LABORATORY
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HEALTH AND SAFETY RESEARCH DIVISION

GENERIC ASSESSMENT OF RADIATION EXPOSURES TO WORKERS IN A PORTABLE SMELTER AND TO THE SURROUNDING POPULATION

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GENERIC ASSESSMENT OF RADIATION EXPOSURES TO WORKERS IN A PORTABLE SMELTER AND TO THE SURROUNDING POPULATION

M. L. Randolph, A. P. Watson, and F. R. O'Donnell

ABSTRACT

A scenario for operation of a proposed portable smelter has been developed by National Lead Company of Ohio to recycle radioactively contaminated ferrous scrap arising from modifications at nuclear facilities of the Department of Energy. The current generic study complements that work by developing tables of radiation dose conversion factors for estimation of external whole-body doses and 50-year whole-body internal dose commitments to routine workers in the smelter and to the public within 50 miles of the smelter. Applications of the tables to specific cases require site-specific source terms consisting of amounts of radionuclides present in scrap metal, separation efficiency for radionuclides, concentration of contaminated airborne particulates, ingested amount of contaminated material, amount of metal released through the stack, etc. Equations relating doses to tabular values and these source terms are developed, and hypothetical sample calculations are given. Assumptions, approximations, and limitations of the methods are discussed as well as nonroutine operations and nonradioactive hazards.

1. INTRODUCTION

National Lead Company of Ohio (NLO) has developed a scenario for the operation of a proposed portable smelter intended for on-site resmelting of slightly contaminated ferrous scrap metal arising from modifications to nuclear facilities of the Department of Energy (Cavendish, 1976; Emison, 1977; Cavendish, 1977*a*). The purpose of this generic study is to provide sets of radiation dose conversion factors for several modes of possible radiation exposure. For example, one set consists of possible external whole-body doses to the various workers resulting from 1 year of processing scrap metal that was initially contaminated with a reference level of 1 ppm by weight of each of 30 radionuclides.

Within the smelter, principal modes of radiation exposure considered are (1) external, from a design-specified set of scrap metal, slag, and metal product sources; and (2) internal, from inhalation of airborne contamination and from ingestion. The relative importance of these exposure modes depends on the radionuclides present (i.e., the types of radiations they emit and their metabolisms) and their concentrations and distributions in or on the various external sources and in air.

Tables of dose factors are given for eight worker categories from processing of about 25,000 tons of scrap iron during a 1-year period. These tables were derived assuming that the workers (1) are exposed to metal scrap, slag, and product metal each containing 1 ppm by weight of each of 30 radionuclide decay chains (assumed to include 20-year build-up of daughter radionuclides); (2) are immersed in air that contains 5 mg/m^3 of iron oxide (Fe_2O_3) particles, which is the chronic threshold limiting value (TLV) set by the American Conference of Industrial Hygienists (1976); and (3) ingest 1 g/year of contaminated material. Equations are given for estimating routine doses in real cases from the tabular values given herein and measured site-specific contamination levels (as multiples of the reference contamination levels).

Outside the smelter, the principal modes of radiation exposure considered from stack emission to the general public are from: surface (i.e., ground) contamination, immersion, air inhalation, and ingestion of food grown near the smelter. A table of dose factors is given for doses from a year's exposure to each of 30 radionuclides via these modes at 1 km from the stack (with air flow given by NLO) as well as a table of relative exposures at various distances up to 72 km. The reference level for the dose factors is an annual release of 1 g of nuclide from the stack. Equations are given for predicting doses in real cases from the tabular values and a list of user-specified, site-specific input parameters.

In addition to presenting the dose factors, this report also discusses the assumptions used, limitations of the treatment, and (briefly) accidents and unusual occurrences. Examples are also given of the methods for application of the dose-factor tables to defined, specific hypothetical problems.

2. DOSE FACTORS FOR ROUTINE EXTERNAL EXPOSURES

Estimates of external, direct radiation doses to workers in the proposed smelter (Cavendish, 1976; Emison, 1977; Cavendish, 1977*a*, 1977*b*) are made, using an upgraded version of the CONDOS computer code (O'Donnell et al., 1975; Killough and McKay, 1976). Necessary input parameters include: assignments of workers in terms of times in various locations and distances from all potential radiation sources, identities and abundances of radionuclides present, sizes and geometries of sources, characterization of any shielding present, and amount of slagging material added. Uncertainties encountered include: time averaging of the exposure durations of workers to the various sources; an unknown assortment of scrap sizes and shapes; the extent to which the scrap has surface or homogeneous contamination; locations and sizes of major scrap, slag, and product piles; and slag disposal practices.

Information supplied by National Lead Company (Cavendish, 1976; Emison, 1977; Cavendish, 1977*a*; Cavendish, 1977*b*) is smelter-design specific. Tables 1 and 2 (time assignments of routine workers) and Table 3 (estimated average distances from work sites to principal radiation sources) were assembled from NLO data. Figure 1 (Cavendish 1976, p. 37) shows the positions assumed for the various work sites. These distances are thought to be conservative (i.e., less than or equal to the real average distances) but cannot be exact in the absence of detailed time and motion studies. For each work site, a selection of sources to be included in dose calculations was made, based on source sizes and distances between sources and workers.

Table 1. Time assignments according to job title and operation of routine workers in smelter

Job title	Operation	Time per shift (hr)
Forklift operator	Charge preparation	1.5
	Scrap drying	1.5
	Slag drum	0.25
	Slag storage	0.25
	Pig stacking	1.0
	Servicing[a]	3.5[a]
	Total	8.0
Crawler crane operator	Charge preparation	8.0
Utility worker	Charge preparation	1.0
	Slagging	1.75
	Pouring	1.75
	Pigging	1.5
	Ladle preparation	2
	Total	8.0
Scrap drier	Sizing	0.5
	Drying	7.5
	Total	8.0
Smelter crane operator	Smelting	8.0
Furnace operator	Smelting	3.0
	Slagging	5.0
	Total	8.0
Pourer-hooker	Slagging	2.75
	Pouring	2.75
	Pigging	2.5
	Total	8.0
Pig stacker	Pig stacking	8.0
Maintenance worker	General maintenance	8.0[a]

[a]Not included in detailed exposure calculations because of unspecified location.

Table 2. Time assignments of routine workers according to site and operation in smelter

Site[a]	Operation	Job title	Time per shift (hr)	Remarks
1	Charge preparation	Crawler crane operator	8	External to building; location and exposure may be site specific
		Forklift operator (2/shift)	0.75	
		Utility worker	0.5	
2	Charge preparation	Forklift operator (2/shift)	0.75	
		Utility worker	0.5	
3	Sizing scrap	Scrap drier	0.5	
4	Drying scrap	Forklift operator (2/shift)	1.5	
		Scrap drier	7.5	
5	Smelting	Smelting crane operator	8	
6	Smelting	Furnace operator	3	
	Slagging	Furnace operator	5	
7	Pouring	Pourer-hooker	2.75	
		Utility worker	1.75	
	Slagging	Pourer-hooker	2.75	
		Utility worker	1.75	
	Slag drum	Forklift operator (2/shift)	0.25	
8	Slag storage	Forklift operator (2/shift)	0.25	
9	Pigging	Pourer-hooker	2.5	
		Utility worker	1.5	
10	Pig stacking	Pig stacker and strapper	8	
11	Pig stacking	Forklift operator (2/shift)	1	
12	Ladle preparation	Utility worker	2	
		Ladle refiner	8	Infrequent operation
13	Servicing	Forklift operator (2/shift)	3.5	Location unspecified
		Maintenance worker	8	Location unspecified
14	Analysis	Laboratory technician	1	

[a]See Fig. 1.

Table 3. Distances of workers from radiation sources

Worker	Work site[a]	Radiation Source[a] (Distance in meters from source)[b] A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Crawler crane operator	1	16.0	4.6	15.0	18.0	18.0	18.0	24.6	21.3	21.3				30.0	34.0				35.0
Forklift operator (two per shift)	1	14.0	1.9	5.5	6.2	7.6	13.6		15.8	12.2			25.0	25.0	21.0		10.6		40.0
	2	36.0	1.9	1.9	3.2	4.7	6.1		10.8	8.6	16.0	20.0	22.0	28.0			15.3		40.0
	8	36.0		5.6	3.2	3.2	5.2	12.8	5.2	3.1	8.7	18.0		27.0			10.0	1.8	5.0
	4	36.0		7.0	5.0	3.0	4.0	9.0	4.0	1.3	10.0	14.0		24.0					40.0
	10	42.0				25.0	21.1	15.7	17.0	31.1	13.0	7.2	5.2	3.6	2.0	10.0			40.0
Furnace operator	6	39.0				11.2	4.4	2.9	6.3	12.8	3.8	5.0	6.5	11.0	14.0	8.0			40.0
Smelter crane operator	5	33.0	16.8	13.8	14.4	9.1	6.2	6.1	3.3	9.1	8.7	6.0	7.5	12.0		4.0			40.0
Pig stacker (two per shift)	10	42.0					21.0	12.6	15.2	22.6	13.0	7.2	5.2	8.0	1.2	10.1			40.0
Pourer-hooker	7	36.0		15.2	14.4	8.2	6.2	2.4	1.5	8.5	2.3	7.4	9.0	13.0		8.0			40.0
	7	36.0		15.2	14.3	8.0	6.2	2.4	2.4	8.5	2.2	7.4	9.0	13.0		8.0			40.0
	9	35.0				13.2	10.5	5.6	6.9	14.3	4.9	1.3	3.2	6.0	12.0	2.6			40.0
Scrap drier	3	30.0	1.3	14.3	9.9	13.8	17.6	23.6	17.4	12.2	26.0	24.0		40.0			1.9		40.0
	4	30.0	3.1	2.5	2.5	1.9	4.7	12.7	6.8	5.5	9.0	14.0	16.0		26.0		15.3		40.0
Utility worker	1	13.0	1.6	4.6	6.1	6.3	13.8		15.8	12.7		25.0	25.0	28.0	30.0		10.7		40.0
	7	36.0		15.8	14.4	8.2	6.2	2.4	1.5	8.5	2.3	7.4	9.0	13.0		8.0			40.0
	7	36.0		15.2	14.3	8.0	6.2	2.4	2.4	8.5	2.2	7.4	9.0	13.0		8.0			40.0
	9	35.0				13.2	10.5	5.6	6.9	14.3	4.9	1.3	3.2	6.0	12.0	2.6			40.0
	12	33.0		15.2		12.1	9.2	6.8	7.2	13.4	5.6	2.0	3.2	6.5	13.5	0.65			40.0

[a]See Fig. 1 for locations of work sites and radiation sources; see Table 2 for time assignments to sites.

[b]Distances given are those used in calculations; other distances are assumed to be infinite.

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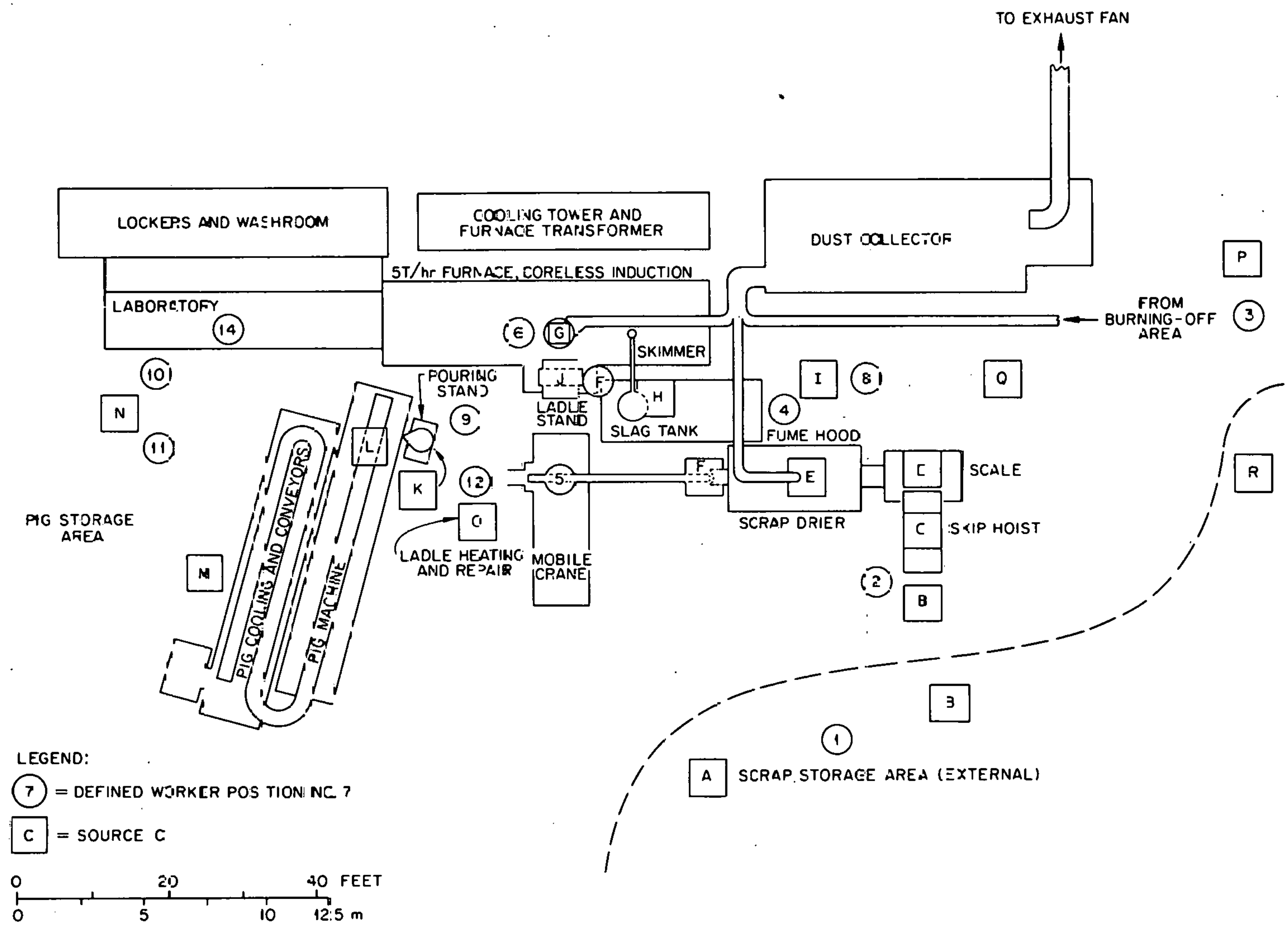

Fig. 1. General plan view of operating facility (adapted from Cavendish 1976).

Only a few simple geometries lend themselves to rigorous, direct calculations. The shapes and orientations of some sources (e.g., the contents of the furnace) may be well defined, but the shapes and orientations of other sources, especially of the scrap pieces, generally cannot be predicted. Hence we have approximated the true geometries by assuming each source to be a cylinder with all exposed persons located on the cylinder axis. The masses of these cylinders were taken from NLO information (Emison, 1977). The heights assigned to the cylinders were equal to or less than the actual average thickness of the sources, and thus the radii of the cylinders were maximized. Orientation of all flat surfaces toward exposed persons tends to overestimate the surfaces to which workers are exposed. We take the density of the product as 500 lb/ft^3 (specific gravity, 7.8), slag as 250 lb/ft^3 (specific gravity, 3.9), and scrap as 50 lb/ft^3 (specific gravity, 0.8), a bulk density which approximates that of automobiles crushed flat. (The contents of the furnace were considered as molten scrap with a specific gravity of 7.8.) A summary of source weights and dimensions is given in Table 4.

To facilitate use of the dose factors calculated in this study when actual source terms are available, all calculations were made for nominal, reference concentrations (1 ppm by weight) of the 30 nuclides listed in Table 5.

Homogeneous contamination is assumed despite the expectation that, for input scrap, most contamination will be on surfaces. If the contamination is primarily on thick-walled, internal surfaces (e.g., pipes and vessels), we might overestimate doses from scrap metal

Table 4. Equivalent sizes of radiation sources
(Real sources were approximated by cylindrical sources of roughly equal mass)

Site	Source	Approximate weight (tons)	Density (g/cm^3)	Radius (m)	Thickness (m)	Kind of source	Remarks
A	Main scrap pile[a]	1.8 + 4[b]	0.8	26.0[a]	20.0[a]	Scrap	Take average weight as 0.6 of total
B, C, D, and F	Tote box, skip hoist, receiving pan, and charge bucket	2	0.8	0.8	1.1	Scrap	
E	Scrap drier	4	0.8	1.2	1.0	Scrap	Maximum weight
G	Furnace	10	7.8	0.8	0.6	Scrap	Maximum weight; scrap composition; density of product
H	Slag quench tank	0.05	3.9	0.3	0.04	Slag	Estimated average weight = 1-hr collection
I	Temporary slag storage	1	3.9	0.4	0.5	Slag	Estimated average weight ≈ 1-day collection
J	Ladle	2	7.8	0.4	0.45	Product	
K	Pouring stand	2	7.8	0.5	0.3	Product	
L	Pigging machine	1	7.8	0.6	0.1	Product	
M	Pig cooling	20	7.8	0.9	0.9	Product	
N	Pig stacking	4	7.8	0.5	0.6	Product	
O	Ladle heat and repair	0.1	7.8	0.38	0.05	Product	
P	Scrap burn-off	4	0.8	1.9	0.4	Scrap	
Q	One slag drum (55 gal)	-	3.9	0.38	0.5	Slag	
R	Semipermanent slag storage	20	3.9	1.0	1.5	Slag	Estimated average weight for 20-day collection

[a] Semicircular cylinder assumed.

[b] Read as 1.8×10^4.

Table 5. Radionuclides considered and some of their characteristics

Nuclide	$t_{1/2}$[a] (days)	Specific activity (Ci/g)	Nuclide	$t_{1/2}$[a] (days)	Specific activity (Ci/g)
C-14	2.1 + 6[b]	4.5	Ru-103	3.9 + 1	3.2 + 4
Na-22	9.5 + 2	6.2 + 3	Ru-106	3.7 + 2	3.3 + 3
Mn-54	3.1 + 2	7.7 + 3	Te-125m	5.8 + 1	1.8 + 4
Fe-55	9.9 + 2	2.4 + 3	Te-127m	1.1 + 2	9.4 + 3
Co-58	7.1 + 1	3.2 + 4	Cs-134	7.5 + 2	1.3 + 3
Fe-59	4.5 + 1	5.0 + 4	Cs-137	1.1 + 4	8.7 + 1
Ni-59	2.7 + 7	8.1 - 2[c]	Ce-144	2.8 + 2	3.2 + 3
Co-60	1.9 + 3	1.1 + 3	Pm-147	9.6 + 2	9.3 + 2
Ni-63	3.5 + 4	5.9 + 1	Th-232	5.1 + 12	1.1 - 7
Zn-65	2.4 + 2	8.2 + 3	U-234	8.9 + 7	6.2 - 3
Sr-89	5.1 + 1	2.9 + 4	U-235	2.6 + 11	2.1 - 6
Sr-90	1.0 + 4	1.4 + 2	Np-237	7.8 + 8	7.0 - 4
Y-91	5.9 + 1	2.5 + 4	U-238	1.6 + 12	3.4 - 7
Zr-95	6.4 + 1	2.2 + 4	Pu-239	8.9 + 6	6.1 - 2
Tc-99	7.8 + 7	1.7 - 2	Am-241	1.6 + 5	3.4

[a]Half-lives from Kocher, 1977.

[b]Read as 2.1×10^{6}.

[c]Read as 8.1×10^{-2}.

sources; if primarily on external surfaces of thick scrap pieces, we might underestimate doses. The magnitude of these effects will depend on the kinds and energies of radiations present. As examples, we calculated the relative exposures for equal amounts of four radionuclides at a common distance (1 m) for the following three geometric classes:

(1) "Surface" geometries consisted of one 10-cm-diam 10-cm-thick copper wafer, two 5-cm-thick stacked wafers, five 2-cm-thick stacked wafers, ten 1-cm-thick wafers and twenty 0.5-cm-thick wafers. In each case the total contamination was constant and equally distributed over the flat surfaces.

(2) "Volume" geometries consisted of either one 10-cm-diam 10-cm-thick cylinder or twenty 0.5-cm-thick stacked cylinders. In each case the contamination was homogeneous with total equal to that for surface contamination.

(3) A "sandwich" geometry (which is an approximation to interior contamination such as in a pipe) consisted of two 5-cm-thick stacked cylinders, with all the contamination on the two interior surfaces.

The results are shown in Table 6. Values for the volume geometry lie between those for the other geometries. For energetic gamma radiations (e.g., those from ^{60}Co) the differences between the assumptions are small, but for low-energy radiations the differences are large.

For our calculations of exposures from contaminated slag, we have assumed the slagging agents to be 1% of the scrap input to the furnace.

Table 6. Comparison of doses from multiple laminar surface contamination vs volume contamination

(Normalization is to the case we generally assume, i.e., single cylinder with homogeneous contamination throughout)

Source geometry			Relative doses for constant amounts of various radionuclides				
Class	Number of pieces	Number of surfaces	Emission Average KeV	C-14 β- 49	Fe-55 E.C.[a], γ 0.6, ∿70% 5, ∿30%	Co-60 β, γ 96,1250	Th-232 Chain, γs
Surface	1	2		490	9970	1.25	1.61
	2	3		245	4977	1.15	1.21
	5	6		98	2000	1.05	1.07
	10	11		49	842	1.03	1.04
	20	21		25	498	1.03	1.03
Volume	1			1.00	1.00	1.00	1.00
	20			1.00	1.00	1.03	1.03
Sandwich	2	1		0.011		0.82	0.78

[a]E.C. = electron capture

This value seems to be at or below the level preferred for removal of impurities and in the lower part of the range of concentrations used in current smelting practice (private conversations with J. H. Cavendish and B. Emison, both of NLO). We also assume that the slag removed from the furnace contains all the slagging agents and none of the iron. If higher concentrations of slagging agents are used or if some iron goes with the slag, there will be more radiation absorbed in and hence less exposure from the slag sources. These considerations have little effect on dose factors for the product.

In considering shielding effects, we have ignored ill-defined or uncertain shields such as a crane between worker and source. The well-defined, "guaranteed" shields that we have included are given in Table 7. We have also included shielding by air with a density of 1 mg/cm^3. For self-shielding and bremsstrahlung production in the sources, we have assumed that the densities are as previously stated and that the effective atomic number is 26 (i.e., iron) for the scrap and product and 13 (i.e., aluminum) for the slag.

We have employed all the factors in modeling workers' external exposures for input to the CONDOS computer code. Table 8 gives detailed, typical results of dose estimates for scrap driers who engage for 1 year in two operations (sizing scrap and scrap drying). The contamination level was taken as 1 ppm of ^{238}U plus daughters in metal scrap, slag, and product metal. From similar calculations for the 30 radionuclides and eight routine worker groups considered, smelter-design-specific tables of dose conversion factors were assembled for scrap metal sources, for slag sources, and for product metal sources.

Table 7. Assigned specific shielding

Source or worker	Material	Thickness (cm)	Density (g/cm^3)	Remarks
		A. Shielding for sources		
Scrap drier	Concrete Iron	6 1	2 7.8	Concrete assumed in place of ceramic
Charge bucket	Iron	1	7.8	
Furnace	Concrete Iron	15 2.5	2 7.8	Concrete assumed in place of ceramic
Slag quench tank	Water Iron	50 0.5	1 7.8	
Ladle	Iron	1	7.8	
Others		0		
		B. Shielding for various workers		
Crawler crane operators	Glass	1	4	Cab partly glass partly iron
Smelter crane operators	Glass	1	4	Cab partly glass partly iron
Furnace operator	Lucite	1	1	
Others		0		

Table 8. Whole-body dose factors for scrap driers working for 1 year in the portable smelter with scrap, slag and product, each contaminated with 1 ppm of U-238. (In millirem)

Kind of source	Source	External direct doses from		
		Sizing scrap	Drying scrap	Total
Scrap	Scrap pile	2.1 - 4[a]	3.2 - 3	3.4 - 3
	Tote box	2.3 - 4	5.9 - 4	8.2 - 4
	Skip hoist	8.8 - 4	9.2 - 4	1.8 - 3
	Receiving pan	3.5 - 6	9.2 - 4	9.2 - 4
	Drier	2.1 - 6	1.5 - 3	1.5 - 3
	Charge bucket	8.2 - 7	1.9 - 4	1.9 - 4
	Furnace	1.5 - 7	8.3 - 6	8.5 - 6
	Scrap burn-off	2.3 - 4	8.3 - 5	3.1 - 4
	Total for scrap	1.6 - 3	7.4 - 3	9.0 - 3
Slag	Quench tank	8.8 - 7	8.9 - 5	9.0 - 5
	Temporary storage	5.4 - 5	4.2 - 3	4.7 - 3
	Semipermanent storage	3.0 - 5	4.5 - 4	4.8 - 4
	Total for slag	8.5 - 5	4.7 - 3	4.8 - 3
Product	Ladle	1.0 - 7	1.4 - 5	1.4 - 5
	Pouring stand	2.4 - 7	1.1 - 5	1.1 - 5
	Pigs cooling	2.7 - 7		2.7 - 7
	Pigging machine		1.1 - 5	1.1 - 5
	Stacking pigs		3.1 - 6	3.1 - 6
	Total for product	6.1 - 7	3.9 - 5	3.9 - 5

[a]Read as 2.1×10^{-4}.

The dose conversion factors are given in Tables 9, 10, and 11, the individual entries of which correspond to the total values given in Table 8. These tabular values include major contributions from scrap and slag but exclude product sources external to the smelter building.

Table 9. Individual whole-body external doses (rem) for 1 year's work at the smelter with 1 ppm of various radionuclides in scrap metal

Nuclide	Workers								Average for 30 workers
	Crawler crane operators	Forklift operators[a]	Furnace operators	Smelter crane operators	Pig stackers	Pourer hookers	Scrap driers	Utility workers	
C-14	5.4 - 3[b]	4.3 - 3	2.6 - 3	2.7 - 3	2.2 - 3	3.0 - 3	1.0 - 2	4.6 - 3	3.8 - 3
Na-22	7.4 + 6[c]	4.1 + 6	3.4 + 6	3.6 + 6	2.4 + 6	3.7 + 6	1.1 + 7	5.0 + 6	4.7 + 6
Mn-54	4.0 + 6	2.3 + 6	1.8 + 6	2.0 + 6	1.3 + 6	2.0 + 6	6.0 + 6	2.7 + 6	2.8 + 6
Fe-55	<1-20	1.0	2.4 - 6	<1-20	6.1 - 8	6.7 - 5	1.7	3.4 - 1	4.7 - 1
Co-58	1.7 + 7	1.0 + 7	7.7 + 6	8.2 + 6	5.5 + 6	8.4 + 6	2.5 + 7	1.1 + 7	1.1 + 7
Fe-59	4.4 + 7	2.7 + 7	2.0 + 7	2.2 + 7	1.4 + 7	2.2 + 7	6.6 + 7	3.0 + 7	2.9 + 7
Ni-59	<1-20	5.4 - 5	9.9 - 11	<1-20	2.5 - 12	2.8 - 9	7.0 - 5	1.4 - 5	1.9 - 5
Co-60	2.1 + 6	1.3 + 6	9.6 + 5	1.0 + 6	6.8 + 5	1.0 + 6	3.1 + 6	1.4 + 6	1.4 + 6
Ni-63	1.4 - 3	3.5 - 3	1.4 - 3	7.9 - 4	1.2 - 3	1.7 - 3	6.9 - 3	2.9 - 3	2.5 - 3
Zn-65	2.8 + 6	1.7 + 6	1.3 + 6	1.4 + 6	9.0 + 5	1.4 + 6	4.1 + 6	1.9 + 6	1.8 + 6
Sr-89	1.0 + 5	6.3 + 4	4.6 + 4	4.9 + 4	3.3 + 4	5.0 + 4	1.5 + 5	6.9 + 4	6.6 + 4
Sr-90	1.4 + 3	8.9 + 2	6.5 + 2	7.0 + 2	4.7 + 2	7.1 + 2	2.2 + 3	9.7 + 2	9.4 + 2
Y-91	1.3 + 5	8.1 + 4	5.9 + 4	6.4 + 4	4.3 + 4	6.5 + 4	2.0 + 5	8.9 + 4	8.6 + 4
Zr-95	3.6 + 7	2.2 + 7	1.6 + 7	1.7 + 7	1.2 + 7	1.8 + 7	5.3 + 7	2.4 + 7	2.3 + 7
Tc-99	1.7 - 4	1.2 - 4	7.6 - 5	8.5 - 5	6.0 - 5	8.6 - 5	2.8 - 4	1.3 - 4	1.2 - 4
Ru-103	1.0 + 7	6.2 + 6	4.6 + 6	4.9 + 6	3.3 + 6	5.1 + 6	1.5 + 7	6.9 + 6	6.6 + 6
Ru-106	4.8 + 5	3.0 + 5	2.2 + 5	2.3 + 5	1.6 + 5	2.4 + 5	7.3 + 5	3.3 + 5	3.2 + 5
Te-125m	5.7 + 2	3.0 + 3	1.3 + 3	3.1 + 2	1.0 + 3	1.5 + 3	5.9 + 3	2.5 + 3	2.0 + 3
Te-127M	3.0 + 4	1.9 + 4	1.4 + 4	1.5 + 4	9.8 + 3	1.5 + 4	4.6 + 4	2.1 + 4	3.8 + 4
Cs-134	1.4 + 6	8.3 + 5	6.2 + 5	6.6 + 5	4.4 + 5	6.8 + 5	2.0 + 6	9.2 + 5	8.8 + 5
Ce-137	3.5 + 4	2.2 + 4	1.6 + 4	1.7 + 4	1.2 + 4	1.8 + 4	5.3 + 4	2.4 + 4	2.3 + 4
Ce-144	1.2 + 5	7.3 + 4	5.4 + 4	5.8 + 4	3.9 + 4	6.0 + 4	1.8 + 5	8.1 + 4	7.8 + 4
Pm-147	1.1	1.0	5.5 - 1	5.6 - 1	4.5 - 1	6.3 - 1	2.1	9.5 - 1	8.9 - 1
Th-232	1.6 - 4	9.7 - 5	7.4 - 5	7.9 - 5	5.2 - 5	8.1 - 5	2.4 - 4	1.1 - 4	1.0 - 4
U-234	2.1 - 5	2.3 - 5	9.3 - 6	1.0 - 5	7.7 - 6	1.1 - 5	4.5 - 5	1.8 - 5	1.8 - 5
U-235	1.1 - 4	7.[illegible] - 5	4.9 - 5	5.4 - 5	3.6 - 5	5.4 - 5	1.7 - 4	7.5 - 5	7.3 - 5
Np-237	6.2 - 2	3.9 - 2	2.8 - 2	3.0 - 2	2.0 - 2	3.1 - 2	9.5 - 2	4.2 - 2	4.1 - 2
U-238	5.9 - 6	3.7 - 6	2.7 - 6	2.9 - 6	1.9 - 6	3.0 - 6	9.0 - 6	4.0 - 6	3.9 - 6
Pu-239	2.2 - 4	1.9 - 4	9.2 - 5	1.1 - 4	7.6 - 5	1.1 - 4	3.8 - 4	1.7 - 4	1.6 - 4
Am-241	9.5 - 1	9.3 - 1	5.0 - 1	5.0 - 1	4.3 - 1	5.8 - 1	1.9	8.9 - 1	8.1 - 1

[a] Values for forklift operators do not include 3.5 hr/shift which they spend in "servicing."

[b] Read as 5.4×10^{-3}.

[c] Read as 7.4×10^{6}.

Table 10. Individual whole-body external doses (rem) for 1 year's work at the smelter with 1 ppm of various radionuclides in slag

Nuclide	Workers								Average for 30 workers
	Crawler crane operators	Forklift operators[a]	Furnace operators	Smelter crane operators	Pig stackers	Pourer hookers	Scrap driers	Utility workers	
C-14	3.6 - 3[b]	3.2 - 2	5.7 - 3	7.8 - 3	3.1 - 3	1.0 - 2	2.2 - 2	8.7 - 3	1.3 - 2
Na-22	1.2 + 6[c]	1.8 + 7	1.8 + 6	3.3 + 6	1.0 + 6	4.1 + 6	6.5 + 6	3.4 + 6	4.0 + 6
Mn-54	6.8 + 5	5.0 + 6	1.0 + 6	1.8 + 6	5.8 + 5	2.2 + 6	3.6 + 6	1.8 + 6	2.2 + 6
Fe-55	5.9 - 7	2.5 + 1	1.6 - 3	4.5 - 8	9.4 - 5	3.2 - 1	4.2	2.2 - 1	5.5
Co-58	2.9 + 6	2.1 + 7	4.2 + 6	7.4 + 6	2.4 + 6	9.3 + 6	1.5 + 7	7.6 + 6	9.3 + 6
Fe-59	7.4 + 6	5.3 + 7	1.1 + 7	2.0 + 7	6.2 + 6	2.5 + 7	3.9 + 7	2.0 + 7	2.4 + 7
Ni-59	2.4 - 11	1.0 - 3	6.4 - 8	1.8 - 12	3.8 - 9	1.3 - 5	1.7 - 4	8.9 - 6	2.3 - 4
Co-60	3.5 + 5	2.5 + 6	5.1 + 5	9.2 + 5	2.9 + 5	1.2 + 6	1.8 + 6	9.5 + 5	1.1 + 6
Ni-63	2.3 - 4	3.3 - 2	4.3 - 3	3.8 - 3	2.3 - 3	7.3 - 3	2.0 - 2	6.3 - 3	1.1 - 2
Zr-65	4.6 + 5	3.3 + 6	6.8 + 5	1.2 + 6	3.9 + 5	1.5 + 6	2.4 + 6	1.2 + 6	1.5 + 6
Sr-89	1.2 + 4	8.8 + 4	1.3 + 4	3.1 + 4	1.0 + 4	3.9 + 4	6.4 + 4	3.2 + 4	3.9 + 4
Sr-90	1.5 + 2	1.1 + 3	2.2 + 2	3.9 + 2	1.3 + 2	4.9 + 2	8.0 + 2	4.0 + 2	4.9 + 2
Y-91	1.8 + 4	1.3 + 5	2.6 + 4	3.6 + 4	1.5 + 4	5.8 + 4	9.4 + 4	4.7 + 4	5.8 + 4
Zn-95	6.0 + 6	4.4 + 7	8.8 + 6	1.6 + 7	5.1 + 6	2.0 + 7	3.2 + 7	1.6 + 7	2.0 + 7
Tc-99	6.6 - 5	5.3 - 4	1.0 - 4	1.6 - 4	5.7 - 5	2.0 - 4	3.8 - 4	1.7 - 4	2.2 - 4
Ru-103	1.8 + 6	1.3 + 7	2.6 + 6	4.6 + 6	1.5 + 6	5.7 + 6	9.4 + 6	4.7 + 6	5.7 + 6
Ru-106	8.0 + 5	5.9 + 5	1.2 + 5	2.1 + 5	6.7 + 4	2.6 + 5	4.3 + 5	2.1 + 5	2.6 + 5
Te-125m	3.5 + 3	5.3 + 4	7.5 + 3	4.2 + 3	3.8 + 3	1.3 + 4	3.4 + 4	1.1 + 4	1.9 + 4
Te-127m	6.1 + 3	4.9 + 4	9.3 + 3	1.5 + 4	5.2 + 3	2.0 + 4	3.5 + 4	1.6 + 4	2.1 + 4
Cs-134	2.3 + 5	1.7 + 6	3.4 + 5	6.0 + 5	1.9 + 5	7.5 + 5	1.2 + 6	6.1 + 5	7.5 + 5
Cs-137	6.0 + 3	4.4 + 4	8.8 + 3	1.6 + 4	5.0 + 3	2.0 + 4	3.2 + 4	1.6 + 4	2.0 + 4
Ce-144	2.2 + 4	1.6 + 5	3.2 + 4	5.6 + 4	1.8 + 4	7.1 + 4	1.1 + 5	5.8 + 4	7.0 + 4
Pm-147	7.5 - 1	6.7	1.2	1.6	6.6 - 1	2.1	4.5	1.8	2.7
Th-232	2.9 - 5	2.0 - 4	4.2 - 5	7.6 - 5	2.4 - 5	9.7 - 5	1.5 - 4	7.8 - 5	9.2 - 5
U-234	2.4 - 5	3.3 - 4	4.0 - 5	5.8 - 5	2.2 - 5	8.5 - 5	2.0 - 4	7.1 - 5	1.2 - 4
U-235	3.7 - 5	2.7 - 4	5.5 - 5	9.7 - 5	3.1 - 5	1.2 - 4	2.0 - 4	1.0 - 4	1.2 - 4
Np-237	1.5 - 2	1.1 - 1	2.2 - 2	3.9 - 2	1.2 - 2	4.7 - 2	7.8 - 2	3.9 - 2	4.8 - 2
U-238	9.0 - 7	6.6 - 6	1.3 - 6	2.3 - 6	7.5 - 7	2.9 - 6	4.8 - 6	2.4 - 6	2.9 - 6
Pu-239	2.2 - 4	2.2 - 3	3.4 - 4	5.6 - 4	3.8 - 4	7.5 - 4	1.4 - 6	6.1 - 4	8.7 - 3
Am-241	1.9	1.6 + 1	2.9	3.8	1.6	4.5	1.1 + 1	3.9	6.3

[a]Values for forklift operators do not include 3.5 hr/shift which they spend in "servicing."

[b]Read as 3.6×10^{-3}.

[c]Read as 1.2×10^{6}.

Table 11. Individual whole-body external doses (rem) for 1 year's work at the smelter with 1 ppm of various radionuclides in product material

Nuclide	Workers								Average for 30 workers
	Crawler crane operators	Forklift operators[a]	Furnace operators	Smelter crane operators	Pig stackers	Pourer hookers	Scrap driers	Utility workers	
C-14	1.1 - 5[b]	2.6 - 4	2.5 - 4	2.4 - 4	3.3 - 3	1.1 - 3	3.3 - 5	1.3 - 3	1.0 - 3
Na-22	1.2 + 4[c]	2.6 + 5	4.0 + 5	2.7 + 5	3.1 + 6	1.1 + 6	4.9 + 4	1.1 + 6	9.7 + 5
Mn-54	6.8 + 3	1.5 + 5	2.2 + 5	1.5 + 5	1.7 + 6	6.2 + 5	2.7 + 4	6.2 + 5	5.4 + 5
Fe-55	1.3 - 8	7.5 - 2	<1-20	<1-20	2.3 - 0	4.2 - 1	3.1 - 5	1.2	6.4 - 1
Co-58	2.8 + 4	6.1 + 5	9.2 + 5	6.3 + 5	7.2 + 6	2.6 + 6	1.1 + 5	2.6 + 6	2.3 + 6
Fe-59	7.3 + 4	1.6 + 6	2.4 + 6	1.6 + 5	1.8 + 7	6.7 + 6	2.9 + 5	6.7 + 6	5.7 + 6
Ni-59	5.3 - 13	3.1 - 6	<1-20	<1-20	9.3 - 5	1.7 - 5	1.3 - 9	5.0 - 5	8.7 + 5
Co-60	3.5 + 3	7.4 + 4	1.1 + 5	7.6 + 4	8.7 + 5	3.1 + 5	1.4 + 4	3.1 + 5	2.7 + 5
Ni-63	6.2 - 6	2.0 - 4	7.6 - 5	8.0 - 5	2.9 - 3	8.3 - 4	1.9 - 5	1.4 - 3	8.6 - 4
Zn-65	4.6 + 3	9.9 + 4	1.5 + 5	1.0 + 5	1.2 + 6	4.2 + 5	1.9 + 4	4.2 + 5	3.7 + 5
Sr-89	1.7 + 2	3.6 + 3	5.4 + 3	3.9 + 3	4.3 + 4	1.6 + 4	6.5 + 2	1.8 + 4	1.4 + 4
Sn-90	2.4	5.2 + 1	7.7 + 1	5.4 + 1	6.1 + 2	2.2 + 2	9.5	2.2 + 2	1.9 + 2
Y-91	2.2 + 2	4.7 + 3	7.0 + 3	4.9 + 3	5.6 + 4	2.0 + 4	8.6 + 2	2.0 + 4	1.7 + 4
Zr-95	6.0 + 4	1.3 + 6	2.0 + 6	1.3 + 5	1.5 + 7	5.5 + 6	2.4 + 5	5.5 + 6	4.7 + 6
Tc-99	3.0 - 7	6.8 - 6	8.5 - 6	7.4 - 5	8.4 - 5	2.9 - 5	1.0 - 6	3.0 - 5	2.6 - 5
Ru-103	1.7 + 4	3.6 + 5	5.5 + 5	3.8 + 5	4.3 + 6	1.6 + 6	6.8 + 4	1.6 + 6	1.4 + 6
Ru-106	8.0 + 2	1.7 + 4	2.6 + 4	1.8 + 4	2.1 + 5	7.4 + 4	3.2 + 3	7.4 + 4	6.5 + 4
Te-125m	5.5	1.6 + 2	3.6 + 1	3.6 + 1	2.1 + 3	6.7 + 2	1.7 + 1	1.1 + 3	6.4 + 2
Te-127m	5.0 + 1	1.1 + 3	1.6 + 3	1.1 + 3	1.3 + 4	4.7 + 3	2.0 + 2	4.8 + 3	4.1 + 3
Cs-134	2.3 + 3	4.9 + 4	7.4 + 4	5.0 + 4	7.8 + 5	2.1 + 5	9.1 + 3	2.1 + 5	2.2 + 5
Cs-137	5.9 + 1	1.3 + 3	1.9 + 3	1.3 + 3	1.5 + 4	5.4 + 3	2.4 + 2	5.4 + 3	4.6 + 3
Ce-144	2.0 + 2	4.3 + 3	6.4 + 3	4.5 + 3	5.0 + 4	1.8 + 4	7.8 + 2	1.8 + 4	1.6 + 4
Pm-147	2.3 - 3	5.4 - 2	5.2 - 2	5.0 - 2	6.9 - 1	2.2 - 1	6.8 - 3	2.7 - 1	2.1 - 1
Th-232	2.7 - 7	5.7 - 6	8.7 - 6	5.9 - 6	6.7 - 5	2.4 - 5	1.1 - 6	2.4 - 5	2.1 - 5
U-234	3.9 - 8	1.3 - 6	9.4 - 7	9.1 - 7	1.8 - 5	5.5 - 6	1.2 - 7	7.8 - 6	5.4 - 6
U-235	1.8 - 7	4.0 - 6	5.8 - 6	4.5 - 6	4.8 - 5	1.7 - 5	7.0 - 7	1.7 - 5	1.5 - 5
Np-237	1.0 - 4	2.2 - 3	3.3 - 3	2.4 - 3	2.7 - 2	9.6 - 3	4.1 - 4	9.6 - 3	8.4 - 3
U-238	9.9 - 9	2.1 - 7	3.2 - 7	2.2 - 7	2.5 - 6	9.1 - 7	3.9 - 8	9.1 - 7	7.0 - 7
Pu-239	3.8 - 7	1.0 - 5	9.9 - 6	9.5 - 6	1.4 - 4	4.3 - 5	1.2 - 6	5.2 - 5	4.2 - 5
Am-241	2.2 - 3	4.9 - 2	4.4 - 2	4.6 - 2	6.2 - 1	2.0 - 1	5.8 - 3	2.4 - 1	1.9 - 1

[a]Values for forklift operators do not include 3.5 hr/shift which they spend in "servicing."

[b]Read as 1.1×10^{-5}.

[c]Read as 1.2×10^{4}.

3. DOSE FACTORS FOR ROUTINE INTERNAL EXPOSURES

As a reference level for computing and compiling dose factors for routine inhalation of radionuclides, we have taken the airborne concentration of iron oxides to be 5 mg/m^3, which is the chronic TLV recommended by the American Conference of Governmental Industrial Hygienists (1976). Other TLVs would apply for the smelting of other metals.

From a review of the literature on measured levels of airborne iron oxides, we conclude that one TLV is a reasonable, generally conservative value to assume in the absence of actual measurements. Substantial variations in airborne particulate concentrations are expected at various locations in a smelter facility.

For each radionuclide, we have listed in successive columns of Table 12 dose factors for: (1) inhalation (50-year dose commitments), (2) immersion (doses), and (3) ingestion (50-year dose commitments). Considerations on which these values are based are given throughout Section 3.

3.1 Airborne Emissions from Secondary Iron and Steel Smelting

3.1.1 <u>Information retrieval</u>

Information retrieval sources used in the search for airborne emission data suitable to calculate air concentrations of contaminated metal included formal literature searches and extensive telephone communications with government agencies. Agencies contacted are listed in Table 13.

Table 12. Immersion doses (rem) from photons to whole body resulting from 1 year's work in smelter building and 50-year dose commitments (rem) to whole body from inhalation and ingestion during 1 work year

Values are based on assuming 5 mg/m^3 of airborne Fe_2O_3 particulates contaminated with 1 ppm of various radionuclides and assuming ingestion of 1 g/yr of dust (4 g/cm^3) contaminated with 1 ppm of radionuclides

Radionuclide	Inhalation	Immersion	Ingestion
C-14	1.7 - 2[a]	<1-20	2.5 - 3
Na-22	7.5 + 2[b]	1.7 + 1	1.1 + 2
Mn-54	1.8 + 2	9.5	6.7
Fe-55	2.0 + 1	2.1 - 3	7.6
Co-58	6.0 + 2	4.7 + 1	5.1 + 1
Fe-59	4.7 + 3	7.5 + 1	1.8 + 2
Ni-59	1.5 - 3	<1-20	1.3 - 4
Co-60	5.9 + 1	3.5	5.1
Ni-63	3.0	<1-20	2.5 - 1
Zn-65	1.4 + 3	7.2	5.4 + 1
Sr-89	3.0 + 3	<1-20	2.5 + 2
Sr-90	2.7 + 2	<1-20	2.3 + 1
Y-91	1.9 + 3	7.9 - 2	8.8 - 2
Zr-95	4.9 + 3	7.3 + 1	1.4 - 2
Tc-99	7.4 - 6	<1-20	8.3 - 7
Ru-103	2.2 + 2	2.8 + 1	2.8
Ru-106	8.5 + 1	1.0	1.1
Te-125m	1.1 + 2	2.0	8.5
Te-127m	1.4 + 2	3.8 - 1	1.0 + 1
Cs-134	6.4 + 2	3.0	9.7 + 1
Cs-137	2.5 + 1	7.4 - 2	3.7
Ce-144	1.8 + 3	3.8 - 1	8.3 - 2
Pm-147	5.6 + 1	<1-20	2.6 - 3
Th-232	2.3 - 4	2.8 - 10	8.1 - 9
U-234	7.3 - 2	1.8 - 8	3.2 - 4
U-235	2.3 - 5	1.1 - 9	1.0 - 7
Np-237	8.4 - 1	6.2 - 7	3.9 - 5
U-238	3.5 - 6	1.5 - 11	1.5 - 8
Pu-239	8.5 + 1	5.2 - 8	1.2 - 3
Am-241	4.1 + 3	2.8 - 4	1.9 - 1

[a]Read as 1.7×10^{-2}.

[b]Read as 7.5×10^{2}.

Table 13. Agencies and associations contacted during search for exposure data

Federal agencies	State and local agencies	Industrial firms and associations
Office of Deputy Director National Institute of Occupational Safety and Health (NIOSH) Rockville, Md. 20850	Department of Air Pollution Control of Knox County Bldg. "C" City Hall Park 307 Locust St. Knoxville, Tenn. 37902	Office of Safety and Health Director American Foundrymen's Society Golf and Wolf Roads Des Plaines, Ill. 60016
Industrial Hygiene Section NIOSH Robert A. Taft Laboratories 4676 Columbia Parkway Cincinnati, Ohio 45226	Division of Air Pollution Control Bureau of Environmental Health Services Tennessee Department of Public Health Cordell Hull Building Nashville, Tenn. 37219	Obenchain Corp. Calumet Division 6911 W. Chicago Ave. Gary, Ind. 46406
Division of Federal Compliance and State Programs Occupational Safety and Health Administration (OSHA) Washington, D.C. 20006		
Office of Air Quality Planning and Standards Environmental Protection Agency Research Triangle Park, N.C. 27709		
Division of Safety Division of Occupational Health Programming OSHA Washington, D.C. 20006		
National Emphasis Program Coordination Center Foundry Program OSHA Washington, D.C. 20006		

Literature searches were performed by the ORNL Ecological Sciences Information Center and the Information Retrieval and Analysis Section of the NIOSH Clearinghouse for Occupational Safety and Health Information in Cincinnati (Robert A. Taft Laboratories, 4676 Columbia Parkway, Cincinnati, Ohio 45226). Data bases searched by the Ecological Sciences Information Center included Biological Abstracts, Bio-Research Index, Government Report Announcements, ERDA Energy Database, Chemical Abstracts, and Nuclear Science Abstracts since 1970. The NIOSH search covered NIOSHTIC (the NIOSH data base) from 1925 to the present time.

Our attention was brought to several useful reference works by the telephone campaign. However, our principal interest was (and still is) in locating field monitoring data from active reprocessing industries. To date, we have been only partly successful.

3.1.2 Description of available exposure data

Collection of data was organized around the flow of scrap metal through the proposed reprocessing facility. All smelting information contained in Table 14 pertains to electric arc or induction furnaces. Available specifics of furnace operation (type, size of charge, stack gas volume, etc.) are included in the text for each step of the process.

3.1.2.1 Material preparation

3.1.2.1.1 *Sizing*. The cutting or shearing of metal scrap to the 46-cm by 61-cm maximum dimensions necessary for processing will be largely completed prior to arrival of scrap at the smelter site. However, some additional sizing may be needed on oversize or awkwardly shaped pieces. Available information on personnel exposure to welding

Table 14. Summary of airborne emissions from secondary iron or steel reprocessing by electric arc or induction furnaces

Smelting operation and location	Approximate measured values							
	Particulates (Fe_2O_3)			Radioactivity			Remarks	Reference
	Lb/product ton	mg/m³	TLV[a]	Particle[b]	dpm/m³	MPC[c]		
Material preparation								
Sizing		4.2	0.8					Johnson, 1959
		10.	2.0					Johnson, 1959
		32.	6.4					Johnson, 1959
		0.9-1.7	0.1-0.3					Kleinfeld et al., 1969
		3.	0.6					Kleinfeld et al., 1969
Drying				α?		17	Source term ≤1500 dpm/cm²	Davis et al., 1957
				α?	17	0.13		McLendon, 1958
	0.4-1.2							Kotzin, 1972
Smelting and refining								
Charging				α?	2-18	0.02-0.14		McLendon, 1958, 1960
Breathing zone	0.4-1.2							Kotzin, 1972
				α	1.5	0.01		Davis, 1977
				β	19-31	4E-4[d]	Uranium daughters?	Davis, 1977
				β	2-3	2E-5	Tc-99	Davis, 1977
Workroom air				α	≤0.9	≤7E-3		Davis, 1977
				β	16-44	5E-4	Uranium daughters?	Davis, 1977
				β	2-5	4E-5	Tc-99	Davis, 1977
Smelting				α?		2.5	Source term ≤1500 dpm/cm²	Davis et al., 1957
				α	31-63	0.4		Starkey et al., 1960
				α	228	1.8		Starkey et al., 1960
				α	1058	10	Radium contamination	Starkey et al., 1961
				α?	1-6	0.01-0.05		McLendon, 1958, 1960
Slagging				α?	7	0.02		Starkey et al., 1960
Pouring and casting								
Pouring				α?	1.1	0.009		McLendon, 1959
				α?	2	0.016		McLendon, 1960
Breathing zone				α	≤3	≤0.025		Davis, 1977
				β	58-120	0.0015	Uranium daughters	Davis, 1977
				β	7-13	8E-5	Tc-99	Davis, 1977
Workroom air		40-60	10					First and Drinker, 1952
				α	≤0.2	≤0.0016		Davis, 1977
				β	66	0.0005		Davis, 1977
				β	7	0.0001	Tc-99	Davis, 1977
Molding				α?	9	0.07		Starkey et al., 1960
		25-40	7					First and Drinker, 1952
General foundry air						2.7	Radium contamination	Starkey et al., 1961
Generalized smelter discharge	5-29							Bates and Scheel, 1974
	10							Bates and Scheel, 1974
	5.7						Lb/ton of charge	Loquercio et al., 1971
	0.01							USEPA, 1973
	10							Vandegrift et al., 1971

[a] We take TLV as 5 mg/m³; thus a measured value of 4.2 mg/m³ = 0.84 TLV.

[b] A question mark in this column indicates an uncertain particle assignment.

[c] These MPC (maximum permissible concentrations) units are for occupational workers:
for alphas from natural uranium, we take the MPC value as 6×10^{-11} μCi/cm³ or 1 α-dpm/m³ = 0.0078 MPC (NCRP, 1959);
for betas from uranium daughters, we take the maximum as 66,000 dpm/m³ (Davis, 1977);
for betas from ^{99}Tc, we take the MPC as 6×10^{-8} μCi/cm³ or 1 dpm = 7.5×10^{-6} MPC (NCRP, 1959);
for alphas from ^{226}Ra, we take the MPC as 5×10^{-11} μCi/m³ (NCRP, 1959, 1963).

[d] Read as 4×10^{-4}.

fumes included literature values for arc welders, flame cutters, and operators of arc air and powder-burning equipment.

By monitoring air within welding hoods, breathing zone concentrations or respirable Fe_2O_3 have been determined for stainless steel arc welders working in fume concentrations ranging from "light" (4.02 to 4.41 mg of Fe_2O_3/m^3 air) to "heavy" (30.5 to 33.5 mg of Fe_2O_3/m^3 air) (Johnson, 1959). Comparable values of 0.7 to 1.7 mg (Fe_2O_3/m^3 of air) have been found within welding hoods during fabrication of stainless steel and black iron (Kleinfeld et al., 1969). Flame cutters without shields were exposed to 3.0 mg of Fe_2O_3/m^3 of air in the same study.

A single reference documents airborne activity levels attained during experimental reprocessing of uranium-contaminated stainless scrap (surface contamination $\leq \frac{150{,}000 \text{ dpm}}{100 \text{ cm}^2}$) (Davis et al., 1957). Additional sizing required cutting with acetylene-oxygen torches. By averaging the accumulated activity found on respirator filters, an estimated airborne activity of 1×10^{-9} μCi/cm³ was determined (Davis et al., 1957). However, no determination was made of particle size or identity throughout the experiment.

3.1.2.1.2 *Drying*. The heating of scrap, both to drive off oils and to preheat the charge, can produce airborne particulates, depending on the method of firing. According to figures published by the American Foundrymen's Society, a top-fired drier can produce 41 lb/ton of product particulates ranging in size between 0 and 20 μ (Kotzin, 1972). Bottom-fired driers are known to give off 1.24 lb/ton of particulates, 75% of which are between 5 and 60 μ in size (Kotzin, 1972).

Experimental reprocessing of ferrous scrap contaminated with undetermined quantities of uranium was performed at the Y-12 Plant in Oak Ridge between 1958 and 1960 (McLendon, 1958). All premelt metal preparations were included in determining the average breathing-zone uranium concentration of 16.8 dpm/m^3. No error terms were given, although this value is the result of 16 individual samples of 4-min duration.

3.1.2.2 Smelting and refining

3.1.2.2.1 *Charging*. Foundry atmospheres monitored during the experimental reprocessing discussed above ranged in activity between 2 and 18 dpm/m^3 (McLendon, 1958, 1960). The minimum values were found in breathing zones of workers actually charging the furnace (number of samples, n, = 16; 10-min collection) and in a general foundry air sampled 9 ft downwind during the charging operation (n = 16, 4-min collection). Samples of general air made on the south side of the furnace during charging equaled 4 dpm/m^3 (n = 4, 10-min collection); while, during the same sampling period, the maximum of 18 occurred on the north side (n = 6, 10-min collection).

Test runs of induction-furnace smelting of contaminated scrap steel were performed at the Union Carbide Paducah facility in September 1977. (Scott, 1977; Davis, 1977; Conrad, 1977). Breathing-zone and general air were monitored for total α- and β-atmospheric contamination caused by uranium, uranium daughters, and ^{99}Tc during charging and pouring. Sampling sites were established at four locations: (1) 6 ft from the furnace lip (at the control panel), (2 and 3) 20 and 30 ft north of the furnace, respectively, and (4) 15 ft west of the furnace. During charging of 12 tons of scrap, the maximum breathing-zone concentrations of 1.6 α-dpm/m^3 uranium and 31 β-dpm/m^3 of uranium daughters occurred at site 1. Maximum general-area values of 0.9 α-dpm/m^3 and 44 β-dpm/m^3 were observed 15 ft west of the furnace. No error terms or physical characteristics of particulates for either the Y-12 or Paducah data were available.

Fume concentrations available from records of the American Foundrymen's Society indicated that similar airborne emission concentrations occur during preheat drying and charging (Kotzin, 1972).

3.1.2.2.2 *Smelting*. All available quantitative information on fume escape to the work area during a melt is the result of radiological monitoring during experimental reprocessing. No corresponding physical characterization of captured particles is available.

Samples of the gas stream directly over a 7-ton top-loading furnace during melting of uranium-contaminated scrap attained a maximum concentration of 1.5×10^{-10} μCi/cm^3 (Davis et al., 1957). The area immediately surrounding a similar furnace, bottom-charged with 6 to 7 tons of baled ferrous material, ranged in activity between 31 and 63 α-dpm/m^3 (Starkey et al., 1960). Average exposure to the elevated crane operator during the smelting of uranium-contaminated scrap at the latter facility was 228 α-dpm/m^3, averaged over a 40-hr week (Starkey et al., 1960). During smelting of radium-contaminated drums, the crane operator was exposed to 1058 α-dpm/m^3 and 47.3×10^{-11} μCi/cm^3 (Starkey et al., 1961). General foundry air activity during the Y-12 experiment ranged between 1 and 6 dpm/m^3 averaged over the entire smelting heat (n = 10 and 9, with collection times of 30 and 10 min respectively) (McLendon, 1958, 1960).

When the charge is composed of uncontaminated metal scrap, emissions from the meltdown period of electric arc furnace smelting are largely Fe_2O_3, ZnO, and volatiles from any remaining grease and oil. Thermal decomposition of lubricants can produce significant amounts of the carcinogen, benzo(a) pyrene (Bates and Scheel, 1974).

3.1.2.2.3 *Slagging*. The single value for emissions during this process is the average alpha dust concentration at the site most frequented by slagging personnel (Starkey et al., 1960). The number of samples collected and particle characteristics were not reported.

3.1.2.3 Pouring and casting

3.1.2.3.1 *Pour*. Fumes produced during pouring and casting are composed of (1) metal oxides formed as molten metal is discharged through air and/or (2) decomposition products of mold resins and oils. During a complete heat, the emission rate of the pour/cast cycle is the lowest.

During the Y-12 reprocessing experiment previously outlined, samples of general air collected 10 ft from the pouring operation attained a maximum of 1 dpm/m^3 (n = 12, 15-min collection). Simultaneous sampling in the breathing zone of the crane operator averaged 1.2 dpm/m^3 (n = 4, 15-min collection) (McLendon, 1958). In a later experiment, the average of seven general air samples of 10-min duration equaled 2 dpm/m^3 (McLendon, 1960).

Radioactivity values from the Paducah induction furnace smelting operation were greatest at 6 ft from the furnace lip (at the control panel) for both α- and β-particles during pour 1 (3.2 α-dpm/m^3 and 120 β-dpm/m^3). The only general-area site monitored during the pour was near an office located 30 ft north of the furnace (Scott, 1977; Davis, 1977; Conrad, 1977). Values at this site equaled 0.2 α-dpm/m^3 and 16 β-dpm/m^3. No error terms or physical characterizations of particulates for either the Y-12 or Paducah facility were available.

By converting field-collected particle counts to weight determinations, First and Drinker (1952) of the Harvard School of Public Health estimated ranges of particulate concentrations for a number of industrial situations. On the assumption that 0.1 mg is equivalent to 5×10^6 particles, the authors estimated workroom air during pouring to contain 40 to 60 mg particulates/m^3 (First and Drinker, 1952).

3.1.2.3.2 *Mold*. Ferrous casting can emit quantities of fine particulates and organic pyrolysis products, depending on the temperature and composition of the mold (Bates and Scheel, 1974); however, neither of these factors is now known.

Available data for dust emission during this process include the value of 9 α-dpm/m^3 measured at the molding site in an experimental uranium-contaminated scrap reprocessing unit (Sect. 3.1.2.2.2) (Starkey et al., 1960). This value is the result of averaging readings collected at personnel sites over a 40-hr week.

Workroom air during molding in a facility processing uncontaminated material can attain a fume concentration of 25 to 40 mg/m^3 (First and

Drinker, 1952). As before, the working assumption is that 0.1 mg of dust equals 5×10^6 particles.

3.1.2.4 General foundry air

The single entry under this heading includes fume concentration of undetermined origin in the workplace. This particular 7-ton bottom-charged arc furnace used radium-contaminated drums as feed material. Continuous monitoring of dust at five sites resulted in an average foundry exposure of 16×10^{-11} μCi/cm^3. Error terms, numbers of samples, and source term activity were not published (Starkey et al., 1961).

3.1.2.5 Generalized smelter discharge

Under this heading are included composite data collected for the entire melt. The usual range for electric furnaces is between 4.5 and 29.4 lb of particulate per ton of melted steel, although the average quantity is assumed to be around 10 lb/ton (Bates and Scheel, 1974; Vandegrift et al., 1971). These values are based on extensive surveys of literature, industrial associations, and government agencies. No error terms were included.

Emission inventory files maintained by the Chicago Department of Air Pollution Control indicate that the average uncontrolled discharge from 5- to 20-ton capacity electric steel melting furnaces is 5.7 lb/ton of raw material processed. Average uncontrolled emissions from smaller (<5-ton) or larger (50- to 75-ton) furnaces are 10.6 and 9.6 lb/ton respectively (Loquercio et al., 1967).

A single reference exists documenting uncontrolled particulate discharge from electric induction furnaces (USEPA, 1973). The reported value of 0.1 lb/ton does not include any consideration of oxygen lancing or oiliness of the scrap as factors altering total emission.

3.1.3 Choice of values

From examination of field data included in the preceding sections and summarized in Table 14, we conclude that accessible information defining personnel exposure to airborne particulates is incomplete at best, especially so for electric induction furnaces.

Presumably, exposure levels will fluctuate widely, depending on physical characteristics of scrap charge, input contamination levels, ventilation rates, temperature of drier and smelter fume, degree of personnel experience, general housekeeping, etc. The variations given in Table 14 may in part reflect such parameters. Comparison of the values of airborne emissions in units of a radiological unit (MPC) for occupational workers versus emissions in terms of a particulate unit (TLV) suggests that the radioactivity generally has been controlled better than have the strictly particulate emissions found in smelters. Therefore, as the contractor will be required to comply with TLVs for airborne metals in workroom air, it was decided that the present evaluation would utilize 1 TLV as our reference unit on which to base tables of inhalation doses. Obviously, multiple TLVs simulate relatively dusty operations and fractional TLVs cleaner procedures. Since steel scrap was specified in the scenario, iron oxide fume is the airborne material of concern. The time-weighted average and short-term exposure limits for iron oxide fume are 5.0 mg/m^3 and 10.0 mg/m^3 respectively. We use the smaller value.

3.2 Dose Factors for Inhalation and Immersion

The real levels of airborne particulates will vary throughout the smelter, but in an, as yet, unknown way. Hence as our reference level of airborne material we use 1 TLV and assume it is uniformly applicable for all routine workers in the smelter building. From application of the CONDOS code, we give in Table 12 immersion dose factors and 50-year whole-body dose commitment factors resulting from 1 year's work in the smelter atmosphere containing 1 TLV of particulates contaminated with 1 ppm of the various radionuclides. Regardless of the concentration of airborne particles, the inhalation dose commitment is greater than the immersion dose for each radionuclide by at least an order of magnitude. Limitations (discussed in Sect. 4.1) of assuming that the concentrations of radionuclides in airborne particles are the same as in scrap apply to use of values given here. If respirators are used (Cavendish, 1976), inhalation of particulates and the consequent doses will be reduced by perhaps a factor of 100.

3.3 Dose Factors for Ingested Radionuclides

We treat ingestion of radionuclides from three pathways: (1) indirectly from inhalation of contaminated air, (2) from foodstuffs grown on contaminated soil and/or in contaminated air, and (3) from dirty eating circumstances. The indirect, internal dose commitment via ingestion of inhaled particles is included in the inhalation dose commitment factors already given (Sect. 3.2); the dose commitment from foodstuffs grown on contaminated soil is discussed in Sect. 5.2. Here we consider ingestion and dose commitment arising from dirty eating circumstances.

Actual values will probably vary widely depending on cleanliness of the washroom, availability of a clean lunchroom, uniforms and gloves, and employees' personal habits. If eating and drinking in the smelter are effectively prohibited, as is the usual health physics requirement for radiation work areas, ingestion will be greatly reduced. As a reference level, we take an annual ingestion of 1 g of dust or 1 μg of radionuclide. This value would result from daily ingestion of 1 mm^3 of dust of specific gravity 4 contaminated with 1 ppm of nuclide and may be compared with Duggan and Williams' (1977) report of values, obtained by themselves and others, equivalent to 2.5 to 25 g of dust ingested per year by young children living near dusty streets. Using Table 4-3 from the INREM code (Killough and McKay, 1976) and Table VII from Kocher (1977), we calculate the 50-year whole-body dose commitments given in Table 12 for annual ingestions of 1 μg of the various radionuclides.

4. APPLICATION OF DOSE FACTORS FOR ROUTINE SMELTER WORKERS

4.1 Method

In preceding sections we have given dose factors for potential routine exposures of workers at the proposed smelter. Tables 9, 10, and 11 give external, direct dose-conversion factors for different workers from scrap, slag, and product contaminated with various radionuclides; Table 12 gives internal dose-conversion factors for inhalation and ingestion of the nuclides and dose factors for immersion in contaminated smelter air.

The dose factors are based on the following reference levels: (1) scrap metal, slag, product, and airborne material (Fe_2O_3) are each contaminated with 1 ppm of the indicated radionuclide; (2) the amount of contaminated, airborne material is 5 mg of iron oxide per cubic meter of air; and (3) workers ingest 1 g of contaminated material per year. Thus in real cases, data are needed for: (1) concentration of each radionuclide in the scrap metal in terms of parts per million by weight; (2) the fraction of each nuclide which smelting separates into product and slag; (3) a generalized contaminated airborne concentration of Fe_2O_3 on localized airborne concentrations; and (4) the amount of contaminated material ingested. Given these data, one can readily apply the following multiplicative factors to the tabular values in estimating doses or dose commitments. Obviously, the total dose to any worker is the sum of his doses from particular nuclides.

To treat the calculation analytically, let C be the concentration in parts per million of a particular radionuclide in the scrap; C_A be the concentration of airborne Fe_2O_3 in TLV units; T_n be the tabular value for the nuclide and appropriate pathway in Table n; and Ing the amount (g) of airborne particles ingested per year. The calculated inhalation dose commitment, D_I; immersion dose, D_{im}; and ingestion dose commitment, D_{ig}; for the nuclide are then:

$$D_I = C \times T_{12} \times C_A \; ; \tag{1}$$

$$D_{im} = C \times T_{12} \times C_A \; ; \tag{2}$$

$$D_{ig} = C \times T_{12} \times C_A \times Ing \; . \tag{3}$$

Implicit in these equations is the assumption that radionuclide concentration in airborne particles equals the initial bulk concentration in parts per million by weight for the scrap metal. These equations therefore tend to underestimate the following doses: (1) that arising from scrap in which the airborne material comes largely from surfaces that contain the contamination rather than the bulk metal, and (2) that arising from slag in which radioactivity is concentrated by the slagging process. The same equations tend to overestimate the airborne contamination arising from the product metal when the slagging process is effective.

Next let E be the efficiency for removal of the nuclide by smelting (e.g., if E = 0.9, 90% of the nuclide goes with the slag and 10% with the product) and S be the ratio of smelting agents to charge (which we have taken as 0.01 in computing Table 10). The calculated external, direct doses for various workers from scrap, slag, and product are:

$$D_{\text{scrap}} = C \times T_9 \ ; \tag{4}$$

$$D_{\text{slag}} = C \times T_{10} \times E/S \ ; \tag{5}$$

$$D_{\text{product}} = C \times T_{11} \times (1-E) \ . \tag{6}$$

These relations are approximations, good to less than 10% for concentrations up to 1000 ppm. As mentioned previously, our tabular values, T_{10}, which enter into Eq. (5) become poor approximations if S differs much from 0.01. If the smelting efficiency is unknown, the conservative approach is to set $E = 1$ in Eq. (5) and set $E = 0$ in Eq. (6). This amounts to assuming both that all the contamination goes with the slag and that all goes with the product.

4.2 Sample Calculation

As a specific example of the calculation of doses, consider the hypothetical case of a forklift operator working at the smelter for 1 year while scrap iron that is contaminated with 50 ppm (by weight) of natural uranium and with 2 ppm of ^{99}Tc is being processed. The efficiency of the smelting process is assumed to be 95% for uranium and 40% for technetium. The airborne concentration of Fe_2O_3 is assumed to be 0.5 TLV and the amount of ingested material to be 0.2 g/year. In Table 15 all the values that enter the calculations are given. For natural uranium, the relative abundances of ^{238}U, ^{235}U, and ^{234}U must be considered. Taking the values of T_i from the appropriate line and column of the applicable table (9, 10, 11, or 12) and the specified C, S, and E values, we calculate each kind of dose using Eqs. (1) through (6). The results for this hypothetical case are given in Table 15.

Table 15. Sample calculations of doses for the hypothetical case of a forklift operator (See text for details)

Nuclide	C (ppm)	Dose calculated and equation number	T	E	C_A	*Ing*	External dose (rem)	50-year internal dose commitment (rem)
U-238	50	Inhalation (1)	3.5 - 6[a]		0.5			8.8 - 5
		Immersion (2)	1.5 - 11		0.5		3.8 - 10	
		Ingestion (3)	1.5 - 8		0.5	0.2		7.5 - 8
		Scrap (4)	3.7 - 6				1.9 - 4	
		Slag (5)	6.6 - 6	0.95			3.1 - 4	
		Product (6)	2.1 - 7	0.95			5.3 - 7	
		Totals for U-238					5.0 - 4	8.8 - 5
U-235	0.35	Inhalation (1)	2.3 - 5		0.5			4.0 - 6
		Immersion (2)	1.1 - 9		0.5		1.9 - 10	
		Ingestion (3)	1.0 - 7		0.5	0.2		3.5 - 9
		Scrap (4)	7.1 - 5				2.5 - 5	
		Slag (5)	2.7 - 4	0.95			9.0 - 5	
		Product (6)	4.0 - 6	0.95			7.0 - 8	
		Totals for U-235					1.2 - 4	4.0 - 6
U-234	0.0028	Inhalation (1)	7.3 - 2		0.5			1.0 - 4
		Immersion (2)	1.8 - 8		0.5		2.5 - 11	
		Ingestion (3)	3.2 - 4		0.5	0.2		9.0 - 8
		Scrap (4)	2.3 - 5				6.4 - 8	
		Slag (5)	3.3 - 4	0.95			8.8 - 7	
		Product (6)	1.3 - 6	0.95			1.8 - 10	
		Totals for U-238					9.5 - 7	1.0 - 4
Tc-99	2	Inhalation (1)	7.4 - 6		0.5			7.4 - 6
		Immersion (2)	-		0.5			
		Ingestion (3)	8.3 - 7		0.5	0.2		1.7 - 7
		Scrap (4)	1.2 - 4				2.4 - 4	
		Slag (5)	5.3 - 4	0.4			4.2 - 4	
		Product (6)	6.8 - 6	0.4			8.2 - 6	
		Totals for Tc-99					6.7 - 4	7.6 - 6
Totals for all radionuclides							1.3 - 3	2.0 - 4

[a]Read as 3.5×10^{-6}.

5. IMPACTS FROM STACK EFFLUENTS

5.1 Stack Effluents

5.1.1 Previously reported effluents

To evaluate adequately atmospheric effluents originating from processing metals in this smelter, an estimate of stack loss is necessary. Values included in the following discussion have been derived from available literature. Although incomplete, these data represent the current status of field monitoring information from active reprocessing industries. The data will be used to estimate total atmospheric emissions of iron and then to calculate doses. The electric-arc-type furnace has been chosen for ferrous scrap reprocessing because of its ability to convert variable grades of scrap to high-quality finish steel (U.S. Steel, 1957).

The first seven entries of Table 16 represent actual operating data collected from modern fume control systems operating in American Foundrymen's Society (AFS) member facilities (American Foundrymen's Society, 1976). Particulate density of discharged fume from electric arc furnaces is not great because of the large volumes of air required to ventilate the furnace adequately (AFS, 1976). In contrast, total quantity of emitted solids (in kilogram per hour) is substantial. Inasmuch as the majority of electric furnace emissions are <5 μm in diam (Table 17), high-efficiency collection equipment is necessary to reduce discharge to negligible amounts (<0.5 gr/ft^3 of air at standard temperature and pressure) (AFS, 1976). For all examples of AFS electric arc furnaces, except numbers 6 and 7 (Table 16), a rooftop hood was the

Table 16. Characteristics of stack emissions during secondary smelting of iron and steel using electric arc furnaces

Unit	Furnace capacity (tons)	Charge rate (tons/hr)	Stack flow rate (m^3/min)	Stack gas temp (°C)	Emission control	Stack loss (gr/DSCF[a])	Stack loss (kg/hr)	Stack loss (kg/ton charge)	Product	References[b]
1		3.3	742	107	Rooftop hood		6.8	4.6		1
2		25	1784	93	Rooftop hood			1.7		1
3		2.4	546		Rooftop hood		9.5	4.9		1
4		2.5	651	104	Rooftop hood		7.6			1
5		3.9	300	103	Rooftop hood		6.0	5.8		1
6		2 at 37	3964	53	Evacuated shell and electrostatic precipitator			13.8		1
7		5	566	66	Overhead canopy hood		45	18		1
8	61				None	0.1 to 6.0			Steel manu-	2
9					High efficiency scrubber	0.01			facture	
10					Electrostatic precipitator	0.01 to 0.04				
11					Baghouse	0.01				
12	1 at 20		2520 to 3080	121 to 188	None	1.9			Carbon and	
13	plus		9100 to 18200	71 to 110	Canopy hood	0.24 to 0.32	300 to 800		alloy	3
14	2 at 122			51 to 66	Baghouse	0.0017 to 0.0047	2.1 to 1[illegible].7		steels	

[a]Grains per standard cubic foot of dry air.

[b]References: 1. American Foundrymen's Society, 1976;
2. Mayer, 1955;
3. Venturini, 1970.

only form of fume control used. Number 7 furnace incorporated a pivoting, close-fitted overhead canopy hood. Evacuated shell ventilation coupled with an electrostatic precipitator was used by unit 6. Pre- and postcontrol discharge from single furnaces operating under similar conditions can be compared in entries 8 through 11 (Mayer, 1965). The efficiency of differing control equipment can also be evaluated.

Five years of operating experience with three electric arc furnaces in a steelmaking shop were reviewed by Venturini (1970). The fume-control system included a direct-roof evacuation type of water-cooled elbow, and spray chamber at each furnace, damper-controlled canopy hoods, and a glass fabric baghouse. By monitoring at various points within the system, the contribution of individual pieces of control equipment could be determined. These data are presented in entries 12 through 14 of Table 16. Entry 12 includes measurements collected at the opening to the hood duct with all dampers closed. The fume product from all three furnaces plus leakage through canopy hood dampers during tapping and charging prior to baghouse filtering is represented in entry 13. Particulate content of exhaust air from all baghouse compartments is entry 14.

Examples of electric furnace fume characteristics are exhibited in Table 17. The first set of composition data was collected in an electric furnace shop and is thought by us to illustrate the maximum degree of variation (Campbell and Fullerton, 1962). Dust from a baghouse that filters air from two 146-ton units was found to contain the oxides and elements reported in the data of Brough and Carter (1972).

Table 17. Iron and steel foundry emission characteristics
(All values are for electric furnaces except values of Stettler et al., which are for arc welder fume.)

Identity	% of Total	% by Weight	Reference
		Fume composition	
Fe_2O_3	19-44	Yes	Campbell and Fullerton, 1962 in Bates and Scheel, 1974.
FeO	4-10	Yes	
Total Fe	16-36	Yes	
SiO_2	2-9	Yes	
Al_2O_3	1-13	Yes	
CaO	5-22	Yes	
MgO	2-15	Yes	
MnO	3-12	Yes	
Cr_2O_3	0-12	Yes	
CuO	<1	Yes	
NiO	0-3	Yes	
PbO	0-4	Yes	
ZrO	0-44	Yes	
P	<1	Yes	
S	<1	Yes	
C	2-4	Yes	
Fe_2O_3	52.5	Yes	Brough and Carter, 1972
ZnO	16.3	Yes	
CaO	14.4	Yes	
MnO	4.4	Yes	
SiO_2	2.6	Yes	
MnO	1.9	Yes	
Na_2O	1.5	Yes	
Cl	1.2	Yes	
Ignition loss	4.3	Yes	
Balance	0.9	Yes	
Stainless steel	83.9	?	Stettler et al., 1977
Aluminum	4.9	?	
Silicate	4.9	?	
Silica	5.4	?	
Other	1.0	?	
Diameter (μm)			
		Particle size distribution	
0-5	71.9	?	Adams, 1964
5-10	8.3	?	
10-20	6.0	?	
20-44	7.5	?	
>44	6.3	?	
<5	60	?	Hammond et al., 1967
5-10	16	?	
10-20	12	?	
20-44	8	?	
>44	4	?	
<0.5	90-95	Yes	Coulter, 1954 in Bates and Scheel, 1974
0-5	65-75	?	Celenza, 1970
0.01 - 0.4	Smoke		Kotzin, 1972
0.03 - 1.0	Oil vapors		
0-60	Metallic oxides		

Information gathered from AFS foundries further identifies smoke, oxide, and vapor particles that are said to be emitted in "light, moderate, and heavy" quantities respectively (Kotzin, 1972). No additional definition of these terms was given.

Further analysis of arc furnace exhaust indicates that more than 70% of all fume contains the particle size distribution published by Adams in his 1964 survey (Adams, 1964). No background information is available for the distribution estimations of Hammond et al., (1967) and Coulter (1954).

Measured values of generalized smelter discharge, in terms of pounds of particulates per ton of product, are given in Table 14.

5.1.2 Choice of values

Because the contractor must comply with existing emission standards, it was decided that the present evaluation would use national limitations set by the Environmental Protection Agency. Performance standards for new and modified electric arc furnace emissions are stated as follows:

1. Emissions from the control device are limited to less than 12 mg/dscm* (0.0052 gr/dscf) and 3 percent opacity.
2. Furnace emissions escaping capture by the collection system and exiting from the shop are limited to zero percent opacity, but emissions greater than this level are allowed during charging periods and tapping periods.
3. Emissions from the dust-handling equipment are limited to ten percent opacity.

(Federal Register, 1975). Opacity values are measured as equivalent smoke density by use of the Ringelmann Smoke Chart (Kotzin, 1972). Regulations of the state of Tennessee limit discharge from iron and

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*Milligrams per cubic meter of standard dry air.

steel plants to a maximum of 12 mg/dscm of air (0.0052 gr/dscf) (Tennessee Department of Public Health, 1977).

5.2 Dose Factors for Stack Effluents

Radiological impacts from materials released through the smelter stack will depend on the quantities (e.g., mg/dscm of dry air) and the characteristics (e.g., particle size and solubility) of the effluent and on several site-specific factors, which include prevalent meteorological conditions, demography, agricultural practices, and the personal habits of residents and visitors. This assessment cannot address these factors in detail because of their site specificity. However, an approximate method is given for estimating radiological impacts from airborne releases.

Table 18 gives annual average ground-level air concentrations and surface deposition rates of particulate emissions at various distances from the smelter stack. These values were calculated by the AIRDOS II computer code (Moore, 1977) for the following situation: (1) prevalent meteorology is that used in the Liquid Metal Fast Breeder Reactor Environmental Statement (USAEC, 1974), (2) 1 kg of airborne metal is released uniformly during 1 year, (3) the smelter stack has a height of 15 m and a diameter of 0.6 m, and (4) metallic particles are discharged at a velocity of 50 m/sec (B. Emison, National Lead of Ohio, Cincinnati, Ohio, personal communication to A. P. Watson, 1978). The AIRDOS code then uses these air concentrations and surface deposition rates to calculate both annual radiation doses from immersion in contaminated air and from exposures to contaminated ground surface and 50-year dose commitments from inhalation and ingestion of radionuclides.

Table 18. Annual average air concentrations and surface deposition rates from release of 1 kg of metal per year from the portable smelter stack

Distance from stack (m)	Ground-level air concentration (mg/m^3)	Concentration ratio[a]	Surface deposition rate (mg/m^2-sec)	Deposition ratio[a]
100	3.8 - 8[b]	0.88	1.3 - 9	2.50
500	8.0 - 8	1.86	9.7 - 10	1.87
1,000	4.3 - 8	1.00	5.2 - 10	1.00
1,300	3.5 - 8	0.81	4.1 - 10	0.79
2,400	1.8 - 8	0.42	2.2 - 10	0.42
4,000	8.9 - 9	0.21	1.1 - 10	0.21
5,600	5.2 - 9	0.12	6.4 - 11	0.12
7,200	3.4 - 9	0.079	4.3 - 11	0.083
12,000	1.3 - 9	0.030	1.7 - 11	0.033
24,000	3.0 - 10	0.0070	4.4 - 12	0.0085
40,000	7.9 - 11	0.0018	1.4 - 12	0.0027
56,000	3.2 - 11	0.00074	6.6 - 13	0.0013
72,000	1.7 - 11	0.00040	3.8 - 13	0.00073

[a]With respect to value at 1000 m.

[b]Read as 3.8×10^{-8}.

Table 19 gives the annual average whole-body dose or 50-year dose commitment to an individual located 1000 m from the stack via each exposure pathway for the release of 1 g/year of each radionuclide.* Assumptions used in computing the doses include: (1) the individual remains at 1000 m from the stack for the entire year, (2) the individual eats food grown primarily at 1000 m from the stack, and (3) no shielding is provided by buildings or intervening structures. Inspection of Table 19 reveals that for each nuclide the surface (i.e., ground) dose is much greater than the air immersion dose.

5.3 Method for Estimating Doses

To estimate annual average whole-body doses to persons near the smelter, the following parameters are needed:

1. R, number of grams of metal released through the stack during the year (user input),
2. W_n, weight fraction of nth radionuclide contained in the metal (user input),
3. N, number of radionuclides contained in the metal (user input),
4. T_d, fraction of the year the exposed individual is x meters from the stack (user input),
5. D, number of distances from the stack being considered (user input),
6. F_d, fraction of the year during which food is consumed that comes from distance x (user input),

---

*For radionuclide contamination of 1 ppm, this level implies emission of about one-fourth the limit for electric arc furnaces or 3 mg/dscm of air.

Table 19. Dose factors for 1 year of exposure at 1000 m from the smelter stack (In rem per gram of nuclide released)

Nuclide	Whole-body dose		Fifty-year whole-body dose commitment	
	Immersion	Surface	Inhalation	Ingestion
C-14	0	0	0	2.6 - 4[a]
Na-22	4.5 - 3	2.6 + 1[b]	3.1 - 2	3.8 + 1
Mn-54	1.9 - 3	8.5	7.0 - 3	1.3 - 1
Fe-55	7.7 - 8	6.5 - 3	8.3 - 4	4.5 - 2
Co-58	9.3 - 3	1.7 + 1	2.5 - 2	1.2
Fe-59	1.9 - 2	2.1 + 1	2.0 - 1	4.4
Ni-59	4.4 - 12	6.7 - 7	6.9 - 8	9.1 - 6
Co-60	9.6 - 4	5.3	2.4 - 3	1.9 - 1
Ni-63	0	0	1.2 - 4	1.6 - 2
Zn-65	1.4 - 3	5.7	5.9 - 2	6.2 + 1
Sr-89	0	0	1.2 - 1	6.0
Sr-90	0	0	1.1 - 2	7.0 - 1
Y-91	2.1 - 5	2.9 - 2	8.0 - 2	1.5 - 3
Zr-95	9.6 - 3	2.1 + 1	1.5 - 1	5.3 - 3
Tc-99	0	0	3.0 - 10	4.0 - 7
Ru-103	4.8 - 3	5.3	9.0 - 3	3.6 - 1
Ru-106	2.0 - 4	9.5 - 1	3.5 - 3	2.8 - 1
Te-125m	1.1 - 4	6.5 - 1	4.7 - 3	3.2 - 1
Te-127m	1.4 - 5	1.7 - 1	5.6 - 3	6.0 - 1
Cs-134	6.1 - 4	3.5	2.6 - 2	8.7
Cs-137	1.5 - 5	1.0 - 1	1.0 - 3	3.8 - 1
Ce-144	5.0 - 5	2.2 - 1	7.5 - 2	1.6 - 3
Pm-147	0	0	2.4 - 3	6.1 - 5
Th-232	8.6 - 18	6.4 - 13	7.1 - 9	1.7 - 10
U-234	6.9 - 13	4.7 - 8	3.0 - 6	7.3 - 6
U-235	1.0 - 13	1.8 - 9	9.3 - 10	2.4 - 9
U-238	1.2 - 16	2.1 - 11	1.4 - 10	3.5 - 10
Np-237	1.9 - 11	1.5 - 7	3.5 - 5	3.8 - 3
Pu-239	1.9 - 12	1.4 - 7	3.6 - 3	2.3 - 5
Am-241	2.1 - 8	4.3 - 4	1.7 - 1	3.8 - 3

[a] Read as 2.6×10^{-4}.

[b] Read as 2.6×10^{1}.

7. D_n^p, annual average whole-body dose (rem/g) or 50-year dose commitment to an individual located 1000 m from the stack for a release 1 g of nuclide n via exposure pathway p, where p = 1 for inhalation, 2 for immersion, 3 for surface, and 4 for ingestion (Table 19),

8. C_d, ground-level air concentration ratio for distance x (Table 18), and

9. S_d, surface deposition rate ratio for distance x (Table 18).

These parameters are used in the following equations for:

1. fifty-year dose commitments via inhalation:

$$\text{DINH} = R \times \sum_{n=1}^{N} W_n D_n^1 \times \sum_{d=1}^{D} T_d C_d \text{ rem ,} \tag{7}$$

2. doses via immersion:

$$\text{DIMM} = R \times \sum_{n=1}^{N} W_n D_n^2 \times \sum_{d=1}^{D} T_d C_d \text{ rem ,} \tag{8}$$

3. doses via surface exposure:

$$\text{DSURF} = R \times \sum_{n=1}^{N} W_n D_n^3 \times \sum_{d=1}^{D} T_d S_d \text{ rem, and} \tag{9}$$

4. fifty-year dose commitments via ingestion:

$$\text{DING} = R \times \sum_{n=1}^{N} W_n D_n^4 \times \sum_{d=1}^{D} F_d S_d \text{ rem .} \tag{10}$$

The above equations will give reasonable estimates of doses to individuals. However, caution should be used in estimating ingestion doses because of the many variables and ingestion pathways involved. If site-specific demographic, meteorological, agricultural, and personal habit data are available, we recommend that an AIRDOS run (or a similar meteorological code) be made for that case.

5.4 Sample Calculation

If the smelter meets the emission standard for electric arc furnaces (12 mg/dscm of air) and operates 5 days per week and 52 weeks per year, about 3800 kg of metal will be discharged from the stack during the year.* Assume, as in Sect. 4.2, that the metal contains 50 ppm of ^{238}U, 0.35 ppm of ^{235}U, 0.0028 ppm of ^{234}U, and 2 ppm of ^{99}Tc. We wish to estimate the dose to an individual who is located 1000 m from the stack for one-half of the year and at 24,000 m for the remainder of the year. Two cases are considered for ingestion, no food comes from near the smelter, and all food comes from 4000 m from the smelter. Table 20 summarizes the user-supplied input parameters and the results of the calculations. Values for D_n^p, C_d, and S_d are from Tables 18 and 19. Results are obtained with the dose equations. The inhalation calculation is given as an example. From Eq. (7) and Tables 18-20:

---

*Data on generalized smelter discharge given in Table 14 suggest that one may expect about 10 lb of airborne particles per ton of product. The smelter is intended to process about 26,000 tons annually. Hence there will be roughly 1.2×10^5 kg of airborne particles released into the ducts of the smelter annually. To reduce this to 3800 kg requires that the baghouse capture about 97% of the airborne mass. Comparisons of data in Table 16 suggest that this is feasible.

Table 20. Parameters used in and results of sample problem calculations for doses from stack emissions

Results	Parameters	Case 1	Case 2
	R, g/year	3.8 + 6[a]	3.8 + 6
	N	4	4
	W_1 (U-238)	5.0 - 5[b]	5.0 - 5
	W_2 (U-235)	3.5 - 7	3.5 - 7
	W_3 (U-234)	2.8 - 9	2.8 - 9
	W_4 (Tc-99)	2.0 - 6	2.0 - 6
	D	3	3
	T_1, years at 1,000 m	0.5	0.5
	T_2, years at 4,000 m	0.0	0.0
	T_3, years at 24,000 m	0.5	0.5
	F_1, from 1,000 m	0.0	0.0
	F_2, from 4,000 m	0.0	1.0
	F_3, from 24,000 m	0.0	0.0
DINH, rem		3.1 - 8	3.1 - 8
DIMM, rem		8.2 - 14	8.2 - 14
DSURF, rem		3.4 - 9	3.4 - 9
DING, rem		0	2.7 - 8
Total, rem		3.4 - 8	6.1 - 8

[a]Read as 3.8×10^{6}.

[b]Read as 5.0×10^{-5}.

$$
\begin{aligned}
\mathrm{DINH} &= \mathrm{R}(W_1D_1^1 + W_2D_2^1 + W_3D_3^1 + W_4D_4^1)(T_1C_1 + T_2C_2 + T_3C_3) \\
&= (3.8 \times 10^{6})(7.0 \times 10^{-15} + 3.3 \times 10^{-16} + \\
&\quad 8.4 \times 10^{-15} + 6.0 \times 10^{-16})(0.5 + 0 + 3.5 \times 10^{-3}) \\
&= (3.8 \times 10^{6})(1.6 \times 10^{-14})(5.0 \times 10^{-1}) \\
&= 3.1 \times 10^{-8}\ \mathrm{rem}\ . \qquad (11)
\end{aligned}
$$

6. ACCIDENTS AND UNUSUAL CONDITIONS

A worst-case estimate of the consequences of total failure of the ventilation system can be made by assuming that the entire smelter building reaches an equilibrium with airborne particulates equal to that in the exhaust duct before any filtration. Input data used for this calculation include:

10 lb of dust per ton of product	(Vandegrift et al., 1971; Sullivan, 1969; Bates and Scheel, 1974; Bond et al., 1972)
Fe_2O_3, about 50% of dust	(Sullivan, 1969; Bates and Scheel, 1974)
34 tons of product per shift	(Emison, 1977)
3×10^4 ft^3/min of air exhaust	(Cavendish, 1977a).

$$10 \left(\frac{\text{lb dust}}{\text{ton product}}\right) \times 0.5 \left(\frac{\text{lb } Fe_2O_3}{\text{lb dust}}\right) \times 34 \left(\frac{\text{ton product}}{\text{shift}}\right) \times \frac{1}{480} \left(\frac{\text{shift}}{\text{min}}\right)$$

$$\times \frac{1}{3 \times 10^4} \left(\frac{\text{min}}{\text{ft}^3}\right) \times \frac{1}{2.85 \times 10^4} \left(\frac{\text{ft}^3}{\text{cm}^3}\right) \times 454 \left(\frac{\text{gm}}{\text{lb}}\right)$$

$$= 1.88 \times 10^{-7} \left(\frac{\text{gm } Fe_2O_3}{\text{cm}^3}\right) = 188 \left(\frac{\text{mg } Fe_2O_3}{\text{m}^3}\right) \simeq 38 \times \text{TLV} . \qquad (12)$$

Should the exhaust system fail, all fumes be discharged to the building and all fumes be equally distributed, this contamination level might be reached in about 20 min. Hence, well-maintained, automatic emergency power for the ventilation system seems essential regardless of whether or not the final building is air supported.

If a full ladle or slag bucket should burst or overturn and spill its entire contents, the immediate risks include burns, perhaps increased airborne contamination, and a direct radiation source no worse than 10 times that of a typical forklift or charge-bucket load. Should the entire contents of the furnace be intentionally or inadvertently dumped, a sump has been planned to contain the contents (Cavendish, 1977a). The main radiological hazard would probably be a pulse of airborne contamination of unknown magnitude and duration. A fire or explosion in the baghouse or in the scrap drier, if not self-contained, would also produce airborne contamination of uncertain magnitude. Automatic fire protection at these points may be desirable.

Occasional operations that may lead to radiation exposures include: repair and relining of ladle, repair and relining of furnace, and erecting and dismantling of the portable smelter system. Work on the internal surfaces of the ladle and furnace should probably include the use of protective clothing and respirators, and direct exposures should be monitored by a health physicist. Localized doses could possibly be received by workers who pick up contamination through open cuts and/or abrasions.

Because of the lack of essential exposure information, dose estimates for workers engaged in these nonroutine and/or unusual working conditions have not been calculated.

7. LIMITATIONS OF THIS TREATMENT

7.1 Radiological

Our present treatment is of a preliminary, generic nature. For a definitive appraisal of a real smelter operation, careful consideration should be made of:

1. concentrations of radionuclides in and/or on the scrap;
2. airborne particulate levels;
3. actual location and average sizes of the main scrap pile (we have assumed it to be large and quite close to the smelter building) and slag storage prior to disposal or total removal;
4. surface-to-volume ratios for scrap; whether contamination is internal (e.g., either inside pipes or the result of neutron activation) or surface dust and dirt;
5. specific external dose calculations for (1) 3-1/2-hr shift of "service operations" by forklift operators, which could double the values we have given for these workers; (2) other persons (general maintenance workers, foremen, and supervisors) for whom doses could equal the highest doses we have given; and (3) laboratory technicians for whom doses are not expected to be large;
6. service operations in, and removal of materials from, the baghouse;
7. contamination levels expected in, and disposal of, slag tank water;
8. general cleanliness of the operation, which includes good housekeeping of the premises, a clean lunchroom, and company-supplied work uniforms and their laundering;
9. air contamination from diesel powered equipment in the smelter building; and

10. site-specific land uses and population density around the smelter.

7.2 Nonradiological

Because of the scarcity of available information, this evaluation has not adequately addressed the nonradiological airborne hazards of smelter operation. Any further assessment should include this aspect of personnel exposure. However, certain critical processes can be emphasized as sources of concern.

Organic materials that are either used as coatings for molds (pulverized coal, dextrine, pitch, asphalt, and fuel oil) or found as contaminants on incoming scrap (oil and grease lubricants) will undergo destructive distillation when heated (Bates and Scheel, 1974). Of particular concern is the temperature range between 300 and 900°F (about 200 to 600°C) in which the heavy organic molecules of anthracene and benzo(a)pyrene can be produced. Experimental sampling of air near electric furnaces and molding yards has confirmed the presence of significant quantities of the carcinogen, benzo(a)pyrene, in foundry atmospheres (Tanimura, 1968).

During meltdown, emissions from an electric furnace are primarily finely divided metal oxides (Table 16). The proportion of individual oxides in fume is determined by charge composition; for example, galvanized scrap producing large quantities of ZnO, and terneplate steel resulting in significant PbO emission during smelting. Strict attention to fume control is mandatory to avoid metal fume fever and excessive exposure to heavy metals.

Following meltdown, oxygen lancing of molten metal can produce a furnace atmosphere in excess of 80% carbon monoxide (CO) (Davies and Cosby, 1963). To prevent explosion and personnel hazard, these large volumes of CO need either to be diluted with makeup air or to be burned off.

Because of possible lung damage and development of "welders" siderosis, any situation that could result in chronic personnel exposure to iron oxide fumes is a candidate for strict monitoring and control (Kleinfeld, 1969). Critical exposures can occur not only during welding operations, but also by inhaling resuspended dusts.

8. CONCLUSIONS

A methodology has been developed for evaluation of the principal radiation doses to routine workers in the portable smelter, as proposed by NLO for decontamination and reprocessing of iron and steel scrap. Straightforward application of the generic dose factors developed to a site-specific case requires prior knowledge of: concentrations of contaminating radionuclides in the scrap metal, airborne concentrations of Fe_2O_3, effectiveness of smelter in separating radionuclides from product metal, amount of contaminated materials ingested, amount of contaminated emission from the stack, local meteorology, demography, etc. Accuracy of predictions is limited, both by assumptions in the calculations (which are discussed) and by the preceding input factors. Limitations of the treatment, and hence implications for further calculations and procedures for safe operation of the smelter, are given.

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